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CERTAIN SPECIFICS OF QUASI-ISOSTATIC MOLDING (A REVIEW)

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The author considers specifics of the method of quasi-isostatic molding, which is the most perfect, economical, and simple method for molding products from powder materials providing for a high quality of products due to the volume compression of the molding material. The method can be used for molding articles from ceramic, metal, and graphite powders, glass ceramics, ferrite, abrasive materials, and in production of refractory articles.

Isostatic molding is at the moment widely used to manufacture articles from ceramic, graphite, and metal powders, abrasive materials, and refractory products. Various molding media can be used in isostatic molding: liquid, inert gas, elastomers, and also molten metal, glass, or graphite (hot isostatic molding).

The technology most commonly used in practice is hydrostatic molding, in which a liquid is used as a medium transmitting pressure. This method makes it possible to mold plastic, poorly pliable, or nonpliable powdered materials into high-strength articles whose size and shape prevent using other molding methods. Hydrostatic molding allows for molding articles of virtually any height having homogeneous high density.

However, despite its advantages, hydrostatic molding also has some disadvantages which impede the wide implementation of this technology in serial production at the domestic factories. For instance, this method requires an extensive set of machinery: a hydrostat made of specially strong steel, vacuum pumps, a tank for molding liquid, a complex system of high-pressure pipelines, and various measuring devices. All this calls for a large production space and a substantial capital investment. Due to the large weight of the isostat and the existence of sealing connections in pipelines, it is difficult and sometimes impossible to subject the molding powder loaded in the hydrostat to vibration treatment. Consequently, vibration is performed outside the isostat, which sharply decreases the process efficiency. Moreover, in molding large-sized articles, especially from fine-disperse molding powders, it is difficult to carry out vacuum treatment due to the volatility of the powder in vacuum. Additionally installed traps do not always ensure a reliable vacuum-treatment process [1]. Furthermore, isostats usually make it possible to mold articles of the same standard size or of similar sizes.

Recently a new method has been developed for molding ceramic articles, namely, quasi-isostatic molding, which provides for volume (triaxial) compression of material molded [2] and is a simplified variant of isostatic molding combining the advantages of static and hydrostatic molding.

This process takes place in quasi-isostatic molds without using costly isostats. The design, installation method, and operating techniques of these molds are similar to those of standard metal molds; they are installed on machines for isostatic molding.

Molds for quasi-isostatic molding have been designed for application on standard hydraulic or mechanical presses available at ceramic works that traditionally use the static molding method.

The principle of quasi-isostatic molding consists in the fact that the medium transmitting a uniform isostatic pressure is a solid elastic element (made of rubber, synthetic caoutchouc, etc.), which simultaneously serves as a mold part shaping the inner or the outer surface of the article. For instance, in molding a ring, the elastic element is a core that molds the inner cavity of the ring, and in molding a solid cylinder, the elastic element is a bushing.

Since the elastic element in volume deformation transmits the applied pressure to the molding powder similarly to a high-viscosity liquid (quasi-liquid) and after multiple deformations (of the order of hundred of thousands) retains its resistance and reversibility without residual deformations, the pressure of the machine applied to the elastic element via the mold punch is isostatically transmitted to the entire volume of the molded article and ensures its volume compression. Owing to this, the resulting articles have an equal density at any section.

A variant of a quasi-isostatic mold for making vacuum-dense rings from fine-disperse aluminum oxide material VK 94-1 is shown in Fig. 1. The mold consists of a floating steel matrix *1* making it possible to carry out bilateral compression along the axis of applying the molding pressure, a pusher *2*, a cavity filled with molding power *3*, an elastic element that is a molding buffer *4*, a steel punch *5*, and vibrators *6*.

Compression of the powder is implemented by the upper punch that transmits the machine pressure simultaneously to the powder and to the elastic molding buffer. The punch moving upwards in the presence of the floating matrix ensures bilateral compression of an article along the vertical axis. The elastic molding buffer under the applied pressure acts similarly to an uncompressible liquid. While its height decreases, it expands in the diametrical direction, thus compressing the powder along the horizontal axes, i.e., in the radial direction. Thus, the molds for quasi-isostatic molding create the conditions for triaxial volume compression, whereas hydrostatic molding on isostats with permanently inserted molds and on automatic presses only creates the conditions for biaxial compression (along the horizontal axes).

Molds for quasi-isostatic molding provide a combination of standard static (uniaxial) molding and radial isostatic molding. The cross-sectional configuration of articles produced using this method can be round, square, rectangular, oval, etc.

Designers in several countries have repeatedly attempted to develop a technology of volume triaxial compression of powder materials, whose main purpose was to replace the expensive isostatic molding technology, which requires complicated isostats, large production areas, and substantial capital investments. In this context, the conditions for volume compression were developed in metal molds by means of triaxially applied pressure. Such molds consist of a cylinder with three openings perpendicular to the axes and converging in the center. Three hydraulic cylinders exert pressure on the punches inserted in these openings. The triaxial application of molding pressure makes it possible to considerably improve the quality of the product, but due to the complexity of the mold design and operation, this technology was not adopted in practice.

A combined method for compaction of powder materials using the radial isostatic pressure by a liquid via an elastic shell and a simultaneous vertical application of pressure via the upper and the lower metal punches provides for a significant improvement in the density and strength of the molded piece. Whereas in static molding the sample density amounts to 78% of the theoretical value, in hydrostatic molding it is 85%, and in triaxial molding — 94%. The strength of the molded sample increases 1.6 and 3.6 times, respectively.

The first studies of molding ceramic parts in gel were published in 1939 (U.S. Patents Nos. 2152732 and 2169280). Much later other publications described attempts to mold metal powders in gel. The main problem in the specified studies consisted in the fracture of articles, but the reason was not clarified; consequently, this line of molding was not pursued.

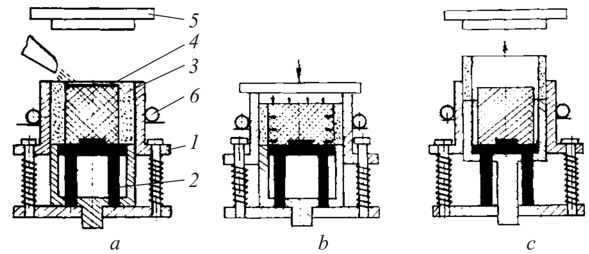

Fig. 1. Scheme of quasi-isostatic molding of rings: *a*) charging of molding powder; *b*) molding of an article; *c*) pushing out and removal of a finished article.

The elastic materials used as shells in the above studies were gelatin, agar-agar, paraffin, wax, epoxy resin, vinyl chloride, and some compositions of natural caoutchouc. However, these materials have low strength, they deeply penetrate into the pores of a molded article, and their removal requires an additional operation. Furthermore, such materials easily penetrate into a narrow clearance between the punch and the matrix, as the consequence of which it becomes impossible to unblock the mold.

Russian researchers along with quasi-isostatic molding of ceramic articles [2] attempted to develop triaxial molding of metal powders. A study of the process of molding samples sized 10×10 mm from metal powders in elastic shells inserted inside standard molds for static molding is described in [3]. The density of the samples molded in elastic shells was 40 – 80% higher than the density of samples made by standard static molding. The author accounts for this fact by the tridimensional application of pressure. However, in making large-size articles, they were unable to obtain the same results as in their laboratory experiments. The researchers assume that the fracture of the articles was the result of the high speed of reversion of the elastic shell to its initial dimensions after the molding pressure was removed.

A. M. Umanskii [4] later investigated some regularities of molding metal powders in elastic shells made of rubber based on natural caoutchouc. The thickness of the wall of an elastic shell was 5 – 7 mm. Laboratory samples sized 10×10 mm were molded from iron and tungsten powders at the unit molding pressure of 100 – 900 MPa. Molding was performed in a steel mold, inside which a mold consisting of elastic elements was inserted. The author believed that such molding method ensures a uniform comprehensive transmission of the pressure to the molding powder due to its isostatic compression.

However, the molding principles described in [3, 4] ought to be regarded not as isostatic (triaxial) molding in which the rubber shell provides for the compression of the powder in the radial direction, but as standard static molding with uniaxially applied pressure. In this case the rubber shell only ensures the elimination of an external friction of the

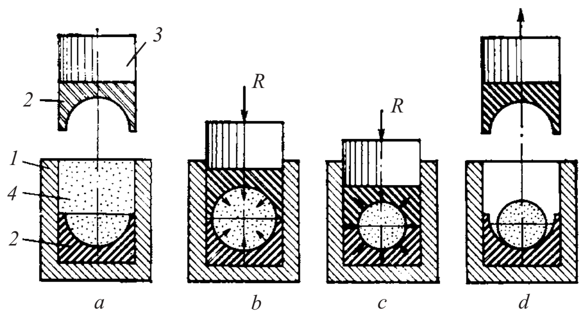

Fig. 2. Scheme of operation of a mold for quasi-isostatic molding of milling balls: *a*) charging of molding powder or a premolded spherical intermediate piece; *b*) start of molding; *c*) end of molding; *d*) return of the punch and the molding buffer to the initial state.

powder against the metal matrix wall, which contributes to improved properties of molded samples.

It is known that in the course of molding in a metal mold, significant heterogeneity is observed in the density of a molded product due to the friction of the powder against the matrix wall, which in sintering leads to deformation, cracking, and other types of defects [5]. Therefore, molding of articles in a rubber shell inserted into a standard metal mold is a promising method for molding powder materials, whose loss of pressure on external friction in a standard metal mold reaches 60 – 90%.

The results of testing of the samples demonstrated the effect of this molding method on the removal of friction of the molded material against the mold walls [3, 4]. Thus, the mechanical strength of the samples grew by 35%, and the molding pressure decreased by 30 – 40% compared with the same parameters in samples molded in metals molds.

The use of rubber shells inside standard molds for static molding cannot ensure the compression of the powder in the radial direction due to the small thickness of the elastic shell, since in the case of applying a uniaxial pressure it is impossible to modify the geometrical sizes of the shell, i.e., to increase its thickness at the expense of its height. In these conditions a thin-walled shell tends to form folds, and a thick-walled shell becomes curved. The same phenomena in an elastic shell under the effect of molding pressure are also noted in [6].

To implement radial compression, the thickness of the wall of an elastic shell should be sufficient to ensure its deformation under an applied pressure. This is a necessary condition for molding powder materials using elastic media.

Since the elastic element (molding buffer) is the most essential component of a mold for quasi-isostatic molding, we investigated the kinetics of elastomers in molding powder materials and the reasons for the destruction of molded articles by the elastic element. The molded piece is destroyed due to the difference between the processes occurring in the elastic element in pressurizing and in its reversion to the initial state. Whereas in developing a pressure, the current stresses (from 0 to 20 MPa) of the molding buffer are balanced by the counterpressure of the pliable molded material, such equilibrium is missing in reversion to the initial state, since the molded material in the final stage transforms into a solid body of invariable shape, which cannot follow the reverse modifications of the elastostressed molding surface of the buffer without a deformation and a disturbance of integrity. Therefore, the sequence of variations in the stresses and the shape of the molding buffer in pressing out does not coincide with the sequence of these variations in the course of developing pressure.

The material of the molding buffer (rubber, synthetic caoutchouc) is not absolutely incompressible in volume (the relative compressibility modulus of rubber is 3000 MPa); therefore, a reversible elastic energy of compression and shape deformation arises in the buffer in the course of molding.

The calculations indicate that a rubber molding buffer of capacity 7850 cm^3 at a pressure of 20 MPa possesses an energy of 95 kJ that is equivalent to a decrease in the kinetic energy of a molded article weighing 7 kg and 13 m high, and one-tenth of this energy in pressing out without using counter-fracture devices is sufficient for destroying any freshly molded article.

For a more detailed study of the behavior of elastic molding elements, an experimental mold with a transparent wall was designed, which made it possible to monitor the modifications in the configuration of the elastic molding buffer with increasing pressure and its elastic reaction after the applied load was removed. The study was performed under molding pressures up to 100 MPa. The obtained data allowed for a correct choice of a method for designing molding buffers for industrial molds to ensure a prescribed geometrical shape of a molded article and made it possible to investigate the mechanism of a destruction of molded pieces by the elastic molding element.

Several variants of stationary molds for industrial production have been designed, which enable the elastic materials to implement both inner and outer compression of the molding powder charged. The variant of two-side compression of molding powder is applicable in molding articles with a substantial wall thickness.

Quasi-isostatic molding can be used in the production of a wide range of ceramic articles. Depending on the effect of applied pressure on molding material, we propose the following classification. The following methods of quasi-isostatic molding can be distinguished: volume, triaxial, radial, and compression with elastic punches.

The method of volume quasi-isostatic molding is applicable in industrial production of such articles as milling balls, cubes, cylinders, parallelepipeds, and other similar bodies of simple geometrical shapes. The molding buffer is designed to be detachable for the purpose of free feeding of molding material and extraction of a molded article (Fig. 2). An elastic molding buffer made of an elastomer (rubber or synthetic caoutchouc) uniformly transmits an applied pressure over the

whole volume of a piece, which creates the conditions for volume isostatic molding.

The method of triaxial quasi-isostatic molding (see Fig. 1) consists in compression of the molding material via an elastic medium in combination with metal punches. The force of the press simultaneously transmitted to the metal punch and to the elastic element of the mold makes it possible to implement vertical compression of the molded material along the axis Z from above and from beneath via metal punches and horizontal compression along the axes X and Y via the elastic medium that converts the force of the press transmitted via the punch into radial isostatic pressure. The elastic element under pressure behaves as an incompressible liquid, becoming shorter in height and expanding in the radial direction, and in this manner together with the punches provides for triaxial compression. The pressure from the press is transmitted in the vertical direction parallel to the longitudinal axis of the molded article.

This method makes it possible to make both hollow (rings, bushes, shells, saggers, crucibles) and solid articles. Compression of powder with an elastic element can be performed both under inner and outer pressure. The variant of two-side compression of molding powder ensuring a uniform volume density of molded articles is applicable in molding articles with a substantial wall thickness.

The method of radial quasi-isostatic molding is intended for molding long solid or hollow articles, such as pipes and rods.

The molding of powder is implemented by means of an outer compression with an elastic molding matrix in the radial direction. This method is based on the principle of outer compression of molding powder with a horizontally applied molding pressure, i.e., perpendicularly to the longitudinal axis of the article. The elastic molding element in this case is a matrix made of rubber, synthetic caoutchouc, or other similar elastomers. The force of the press is transmitted to the elastic matrix filled with a molding powder via metal punches located perpendicularly to the axis and moving towards each other. The metal punches fully embrace the elastic matrix ensuring a uniform radial compression of the molded material along the entire length of the article.

The method of quasi-isostatic molding with elastic punches is the most acceptable for molding flat articles, such as plates of various configurations: disks, wheels, washers, etc. When such articles (especially, large-sized ones) are molded in a horizontal plane using the standard static molding method, i.e., using rigid punches, it is impossible to obtain a homogeneous density. An elastic punch imparts a homogeneous density and high physicomechanical parameters to the article. However, the surface of the articles on the side of the molding elastic punch sometimes requires mechanical treatment. The pressure is transmitted to the molded material from one side and, if necessary, from two sides, i.e., by punches moving toward each other.

In developing the quasi-isostatic molding technology, one of the main problems was the choice of accessible materials for elastic molding elements to ensure the necessary conditions for a compaction of powders and a reliable performance of molds in industrial conditions.,

A number of elastomers have been tested: gelatin, some resins, technical rubber, natural and synthetic caoutchouc.

The studies demonstrated the expedience of using polyurethane elastomers in molds for molding ceramic materials. A polyurethane elastomer SKU-7L was chosen as the optimum materials. This material ensures the production of articles with an equal density throughout the volume and with a smoother and less rough surface. After many years of service of quasi-isostatic molds, no indications of wear were registered in elastic molding elements made of SKU-7L polyurethane, at least after molding 100 thousand articles; no modifications of sizes or deterioration of the molding properties were registered. The surface of the molding buffer is virtually not worn, since in the course of molding, the molding surface of the buffer sags similarly to the molded material at all contact points, therefore gliding friction does not exist between them. The elastomer SKU-7L has high wear resistance and capacity to operate under high pressure (up to 1000 MPa and more). Its strength is 6 – 8 times higher than the strength of rubber, and its specific wear resistance is 3 times higher than that of steel St.3 and 60 times higher than that of epoxy resin [6].

Of all known elastomers, only polyurethane retains its elasticity for a wide range of hardness variations (Shore hardness up to A95 and above). The unique combination of its physicomechanical properties determined the possibility of its application for molding powder materials. Urethane elastomers as structural materials not only replace metals but surpass them in their service properties [7].

For uniform transmission of pressure to a molding powder, the behavior of the molding buffer material should be similar to the behavior of liquid. As a consequence of long-time studies and experiments, the physical principles of this process were investigated, the optimum compositions for elastic molding buffers were selected, and the theory of mold design was developed.

A method for the calculation of a quasi-isostatic mold design was developed using both inner and outer compression of a molding material. All this made it possible to create industrial quasi-isostatic molds, which in their design, installation method, and operation techniques are similar to the standard molds used in static molding. It should be noted that in quasi-isostatic molding, a molded piece exists in a more complex volume-stressed state than in the usual static molding, since the system of forces acting in standard static molding is complemented by the reversible elastic energy of the compression of the buffer volume and the deformation of the buffer shape.

In view of that, special attention in the development of this molding technology was paid to the mold design. As a result, molds were developed for molding plastic ceramic materials (molds operating at low pressures up to 20 – 25 MPa) and for molding nonplastic materials (100 – 200 MPa).

Molds were designed for producing a wide range of products: saggers (round, rectangular, and square) and shells from chamotte and Alundum mixtures; smooth rings of diameter 86, 143, 180, 190, and 250 mm and up to 170 mm high made of aluminum oxide material; milling balls 20, 30, 40, 50, and 60 mm in diameter; pot condensers 170 and 120 mm high; tubes of different standard sizes up to 160 mm long, including tubes with the wall thickness of 1.5 mm; plates of various standard sizes (up to 425 × 425 × 65 mm); rods 17 mm in diameters and 160 mm long, crucibles, and other products [2, 6, 7].

The technology of quasi-isostatic molding of the above listed articles has been implemented at several ceramic works. The process uses the same molding powders that are used in static molding. The molds have been installed on hydraulic and mechanical presses or automated molding machines available at the works. No additional machines had to be acquired. The investment of companies in introducing this technology consisted of the cost of making molds (the molds were mostly manufactured in the mold shops of the factories).

The conditions for quasi-isostatic molding are developed inside the industrial molds during one stroke of the punch, owing to which the molds have a high efficiency that mostly depends on the degree of mechanization of feeding the molding powder into the mold and the removal of molded articles. Some articles can be molded in an automatic mode.

The molding pressure in quasi-isostatic molding is 30 – 50% lower than in usual static molding, since the loss of pressure on external friction is almost nonexistent, as the pressure is applied simultaneously to all external surfaces of the molded material. Consequently, due to a significant decrease in the energy consumed on the friction of the powder particles against the mold wall, a piece molded in this way has higher density and homogeneity than a piece molded in standard metal molds [2, 8 – 10]. M. Yu. Bol'shin demonstrated that the total pressure applied to an article in compressing powder materials is made up of three components.

$$P = P_1 + P_2 + P_3,$$

where P_1 is the pressure used for compacting the powders; P_2 is the pressure consumed to overcome the friction of the powder against the matrix walls; P_3 is the pressure developed at the point of contact of particles in the areas in which the density exceeds the average density of the molded article.

The pressure P_3 arises due to the radial component of the pressure, which results in nonuniform powder density in the article.

In quasi-isostatic pressure, $P_2 = P_3 = 0$, i.e., the applied pressure is used exclusively for compressing the molding powder, which ensures the production of articles with a uniform density over the entire volume under a lower level of pressure.

Quasi-isostatic molding is the most perfect method for molding ceramic articles, ensuring their high quality owing to the triaxial application of pressure. This is the most efficient method of all isostatic molding methods. All work and expense that is required of a company is reduced to designing molds, which are similar to static-molding molds, and producing them in metal. No additional press machinery is needed.

Our experiments in quasi-isostatic and hydrostatic molding of tubes 11 mm in diameter and 125 mm long demonstrated that the cost of the engineering design to implement the quasi-isostatic molding method is 20 times lower than in hydrostatic molding. The cost of acquiring a standard press and designing a mold is lower by an order of magnitude. The time needed to develop and implement the quasi-isostatic molding technology is several times shorter and the production area needed for this technology is substantially smaller. The durability of a rubber shell in hydrostatic molding was 250 cycles, and the durability of a polyurethane molding buffer was more than 100 thousand cycles.

The excellent prospects of this technology were frequently discussed earlier [2 – 12]. It should be noted that in out time the isostatic molding using elastic media remains the simplest and the most universal method of molding.

Quasi-isostatic molding can be widely used for making articles from ceramic, metal, and graphite powders, from glass ceramics, ferrite, and abrasive materials, and in the production of refractories.

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